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## Brief original

# Exploratory study on the bending performance of thermo-hydro-mechanically densified Scots pine (Pinus sylvestris L.) at elevated temperatures

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## Abstract

Thermo-hydro-mechanical (THM) densification is a well-known wood modification procedure for improving the mechanical properties of low-density wood species, but its performance at elevated temperatures is not well understood. The objective of this study was to determine the bending behaviour of densified Scots pine at elevated temperatures. A total of 48 specimens (200 mm (Longitudinonal) × 20 mm (Radial) × 20 mm (Tangential)) were tested to investigate the bending performance under constant temperatures at 25, 50, 125 and 175 °C, respectively. It was found that the modulus of rupture (MOR) and modulus of elasticity (MOE) of both un-densified and densified pine decreased with increasing temperature. However, the densified wood exhibited more brittle shear failure but retained higher MOR and MOE than the untreated specimens treated at the same temperature level. In general, the results demonstrate that densification can be a potentially effective method to retain the mechanical properties of wood at elevated temperatures, thereby having a potential maintain the load-bearing capacity during and after fire.

**Keywords**: Densification, fire safety, timber construction, wood

## Introduction

Thermo-hydro-mechanical (THM) densified wood is rarely used in construction, although its mechanical properties are excellent in many cases (Sandberg *et al.* 2013). One of the reasons is the set-recovery behaviour that may occur in THM-densified wood, resulting in a reduced degree of densification over time. Additionally, the available knowledge on its fire behaviour is insufficient. For wood products, the inherent combustibility is always the main challenge which restricts its role in construction applications (Popescu and Pfriem 2020). Therefore, the implementation of engineering modification processes to improve wood with regards to durability or other properties should not overlook how these processes influence fire safety. Studies on fire performance of densified wood indicate that the densification itself slightly increases the ignition time and reduces the heat release rate (Tran *et al.* 2022, Xu *et al.* 2022, Scharf *et al.* 2024).

Wood starts to lose its strength and stiffness when the temperature reaches approximately 65 °C. According to Eurocode 5, when the temperature of the wood increases from 50 °C to 100

°C, its tension, shear, and compression strength parallel to the grain reduce to 65%, 40%, and 25%, respectively (CEN 2004). Knowledge of the temperature-dependent reduction of strength and stiffness is an important precondition for determining the behaviour of a timber construction capacity during and after a fire event. The unexplored potential high mechanical properties of densified wood at elevated temperatures could provide extra residue load-bearing capacity to ensure structural integrity. This would mean additional time for evacuation, rescue and firefighting during fire. The purpose of this exploratory study is to determine the bending properties of THM-densified Scots pine at different elevated temperatures.

## Materials and Methods

48 straight-grained, defect-free specimens of Scots pine (*Pinus sylvestris* L.) sapwood with dimensions of 200 mm (Longitudinal) × 20 mm (Radial) × 20 mm (Tangential) were prepared from a single log. The specimens were conditioned at 20 °C and 65% relative humidity (RH) until achieved constant mass (approx. 12% wood equilibrium moisture content). The specimens were randomly distributed into two groups: an untreated reference group and a densified group. Each group was divided into sub-groups containing six replicates for bending tests under temperatures of 25, 75, 125, and 175 °C, respectively.

An open-system hydraulic hot-press (Langzauner “Perfect” LZT-UK-30-L, Lambrechten, Austria) was used for the THM densification (Lei *et al.* 2022). The specimens were compressed in the radial direction from 20 to 10 mm in four stages: (I) the hot press was pre-heated to 170 °C, (II) the specimens were placed in the press, and a pressure of 4 MPa was applied for 3 minutes, (III) the temperature of the press was raised to 200 °C and kept for 2 minutes, and (IV) the press was cooled to 60 °C with the specimens remaining under compression at 4 MPa for 5 minutes.

Before the bending test, all specimens were dried at 60 °C and 10% RH for 72 hours. This drying regime resulted in close to 0% wood moisture content, to exclude the influence of moisture level variations on the bending properties. The specimens were sawn in dry conditions to dimensions of 200 mm (Longitudinal) × 10 mm (Radial) × 13 mm (Tangential) for the bending test.

The four-point bending test was based on the EN 408 standard (CEN 2010) and conducted on a universal testing machine (Zwick UTM Z100, Zwick GmbH & Co. KG, Ulm, Germany) with a 100 kN load cell. A climate chamber around the test region was used to regulate the temperature. The specimens were heated to the target temperature (25, 75, 125 or 175 °C) before loading by placing them in the pre-heated climate chamber along with additional twin specimens wired with three thermocouples at middle depth to establish when the core of specimens reached the target temperature (Figure 1). The bending test started 5 min after the target temperature was reached. The specimens were loaded in the radial direction. The tests were done under quasi-static loads at a speed of 5 mm/min, and the modulus of elasticity (MOE) values were specified in the range from 10% to 30% of the maximum load.

**Figure 1.** Test setup for four-point bending test at elevated temperature.

The effects of THM densification on bending performance at each temperature level were analysed based on the one-way analysis of variance (ANOVA) test and Dunnett's method by statistical analysis software JMP (SAS Institute Inc., Cary, NC, USA) at $p < 0.05$.

## Results and discussion

Table 1 shows the physical and flexural properties of untreated and densified specimens. Because the 50% compression ratio was successfully achieved, the density of densified pine was twice of untreated pine. Both the MOE and MOR at all temperature levels were improved significantly by THM densification.

**Table 1.** Physical and flexural properties of untreated and densified specimens.

| | 60 °C, 10% RH | | 25 °C | | 75 °C | | 125 °C | | 175 °C | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Density (kg $m^{-3}$) | EMC (%) | MOR (MPa) | MOE (GPa) | MOR (MPa) | MOE (GPa) | MOR (MPa) | MOE (GPa) | MOR (MPa) | MOE (GPa) |
| Untreated Reference | 513 (15) | 1.93 (0.15) | 159.0 (14) | 13.7 (0.8) | 135.0 (12) | 12.0 (1.5) | 105.0 (24) | 12.6 (0.9) | 88.0 (11) | 10.9 (1.9) |
| Densified | 1012 (40) | 1.63 (0.2) | 248.0 (13) ** | 24.2 (1.9) ** | 211.0 (28) ** | 20.1 (2.5) ** | 155.0 (30) * | 16.7 (1.8) ** | 130.0 (2) ** | 15.1 (0.4) ** |

Data in parentheses, standard deviation. Asterisks denote the significant level of densification on MOE and MOR at each temperature level (* is $p < 0.05$, ** is $p < 0.01$).

Figure 2 shows the loading force versus displacement curves of the specimens at different temperatures. For the untreated reference specimens, the bending force increased close to linearly (elastic zone) and then increased nonlinearly up to the peak force (plastic zone). Subsequently, most post-peak curves of untreated specimens exhibited ductile characteristics due to the progressive damage in the specimens. On the contrary, the post-peak curves of densified specimens showed more brittle rupture behaviour since the bending force suddenly and dramatically dropped after reaching maximum load. The sudden drop of the bending force mainly came from the brittle shear failure without a progressive damage process.

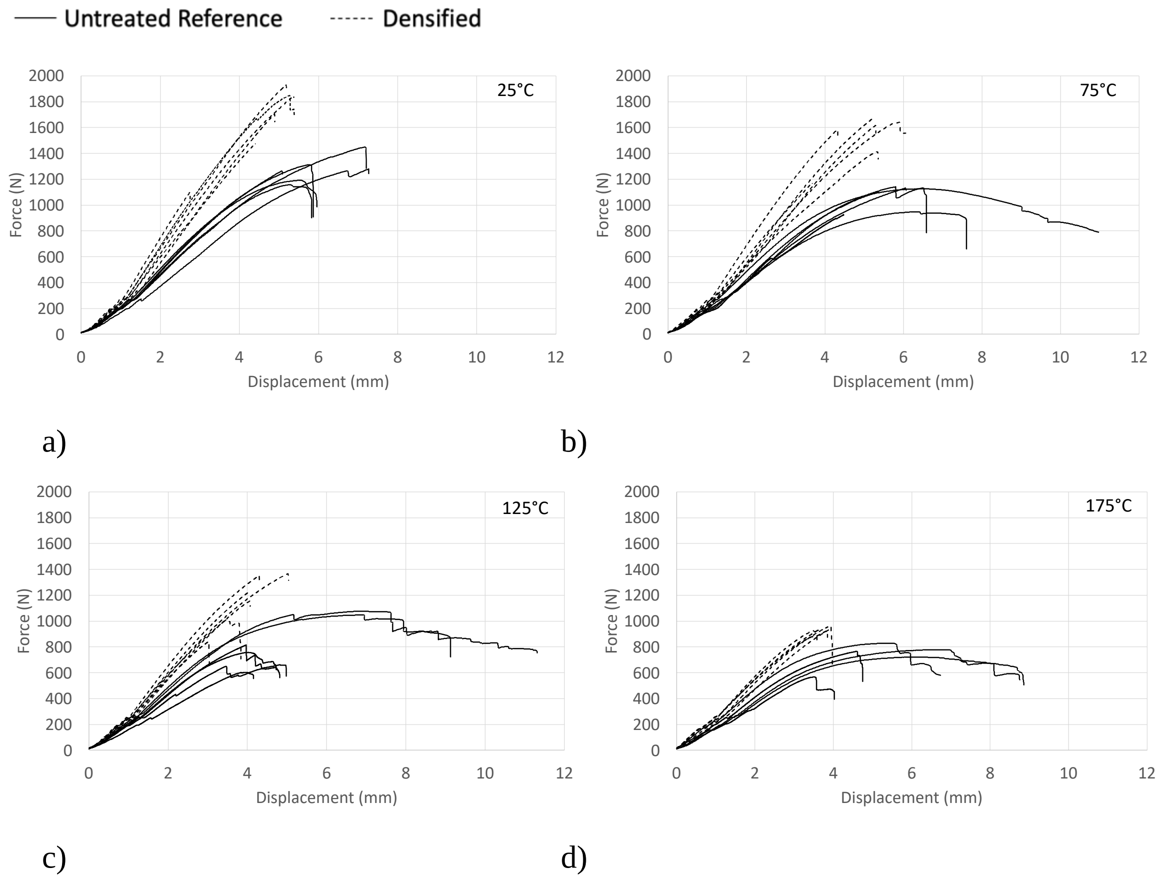
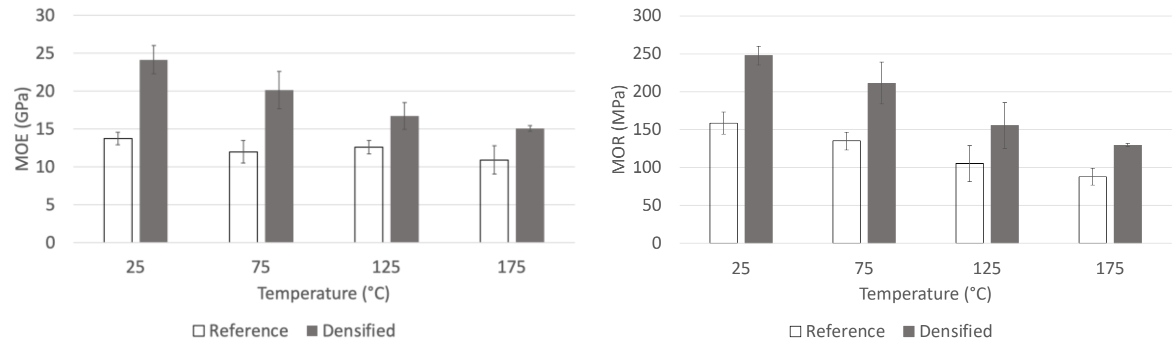



Figure 2. Bending load-displacement curves of untreated reference and densified wood under different temperatures: (a) 25 °C, (b) 75 °C, (c) 125 °C, and (d) 175 °C.

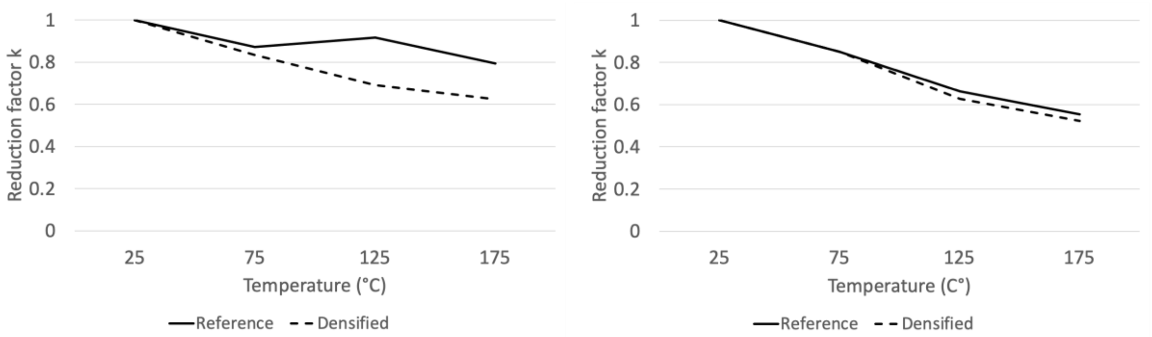
Figure 3 shows the MOE and MOR of untreated reference and densified wood at temperatures from 25 °C to 175 °C. The MOE of the untreated reference specimens had a moderate decrease from 13.7 GPa at 25 °C to 10.9 GPa at 175°C. The MOE of densified wood kept decreasing from 24.1 GPa to 15.1 GPa over the entire temperature range. Moreover, Figure 4a shows the reduction factor (CEN 2004) of MOE of densified wood decreased more sharply than untreated reference wood at elevated temperature, but it should be noted that the MOE of densified wood were obviously higher than the MOE of untreated reference wood at all same temperature levels. The MOE of densified wood at 175°C was even higher than the MOE of untreated reference wood at 25 °C.

The reduction factor of bending strengths from 25 °C to 175 °C is shown in Figure 4b. It can be seen that the MOR of both untreated reference and densified wood generally decreased in a similar way with the increase in temperature, but the MOR of densified wood was always higher than that of untreated reference wood at the same treatment temperature (Figure 3b). The MOR of densified wood at 125°C was at the same level as the MOR of untreated reference wood at 25 °C.




(a) (b)

Figure 3. Temperature-dependent bending performance with standard deviations for the tested temperatures: (a) MOE and (b) MOR.




(a) (b)

Figure 4. Temperature-dependent reduction factor k for bending performance: (a) MOE and (b) MOR.

A deeper and more detailed study on the fire performance including the reaction to fire and mechanical properties at the evaluated temperature of densified wood with different densification process parameters is ongoing. In addition, the compatibility with fire-retardant coatings and impregnation will be studied.

## Conclusion

In this study, four-point bending experiments were carried out on untreated and densified Scots pine at elevated temperatures between 25 °C to 175 °C. Ultimately, the goal is to apply THM-densified wood into engineered wood products with enhanced mechanical and fire performance. For both the untreated and the densified pine, the modulus of elasticity (MOE) and modulus of rupture (MOR) decreased with the increasing temperature. Under the same temperature, the retention factor of the MOE was significantly higher than that of the MOR. The densification not only increased the bending performance at 25 °C but also retained better bending performance than untreated pine at elevated temperatures from 25 °C to 175 °C.

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## Disclosure statement

No potential conflict of interest was reported by the authors.

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